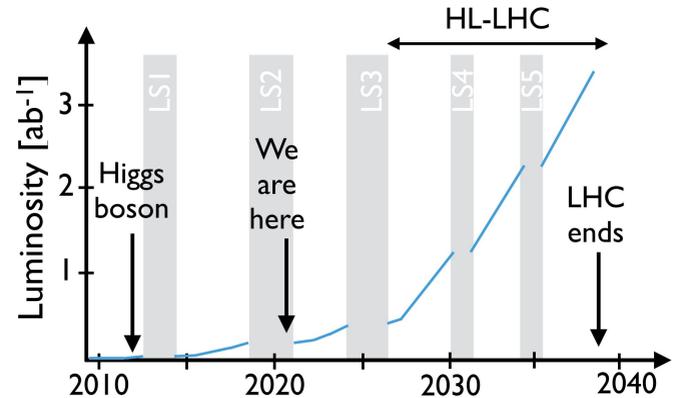


# The Forward Physics Facility at the LHC.

Felix Kling  
Brookhaven Forum 2021  
11/03/2021



# Motivation.



The LHC will soon start to prepare for its high-luminosity phase.

Is there anything we miss?

Can we do something to enhance its physics potential?

If yes, we need to do it now or lose them for many decades.

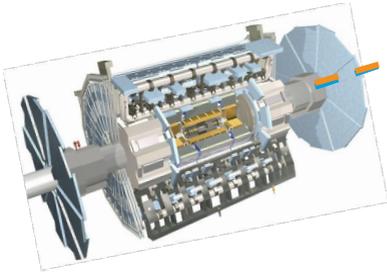
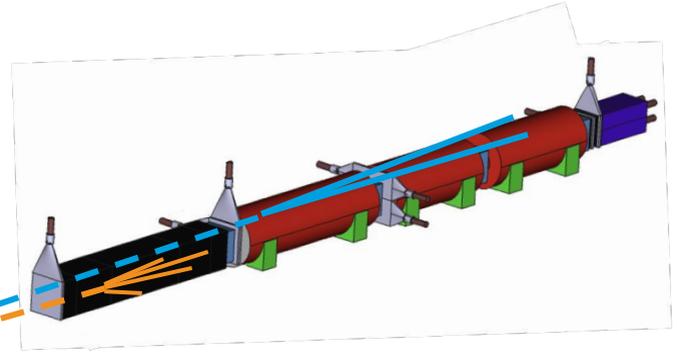
**Proposal:** Explore a rich BSM and SM physics program in the far forward region to greatly expand the LHC physics potential.

# Motivation.

Light hadrons are copiously produced in the far-forward direction of LHC:  
 $4 \cdot 10^{17} \pi^0$ ,  $6 \cdot 10^{16} \eta$ ,  $2 \cdot 10^{15} D$ ,  $10^{13} B$  within 2mrad of beam

## Searches for New Physics:

- \* light LLPs:  $A'$ ,  $S$ , ALPs, HNLs, iDM, ...
- \* produced via  $\pi^0 \rightarrow \gamma A'$ ,  $D \rightarrow K \ell N$ ,  $B \rightarrow X_s S$ ,
- \* lifetime  $\sim 500\text{m}$



## SM Measurements:

- \* pp collision produce forward neutrino beam
- \* produced via  $\pi \rightarrow \nu \mu$ ,  $K \rightarrow \nu e$ ,  $D \rightarrow \nu T$
- \* TeV energies

**Experimental Program:**  
**FASER - FASERv - SND@LHC - FPF**

Searches for BSM physics:  
LLPs - DM - mCPs

SM Measurements:  
Neutrinos - QCD - Cosmic Rays

# Neutrinos at the LHC.

Neutrinos detected from many sources,  
but not from colliders.

But there is a huge flux of neutrinos in the forward direction,  
mainly from  $\pi$ , K and D meson decay. [De Rujula et al. (1984)]

ATLAS provides an **intense** and **strongly collimated** beam of  
**TeV-energy** neutrinos along **beam collision axis**.

NEUTRINO AND MUON PHYSICS IN THE COLLIDER MODE OF FUTURE ACCELERATORS<sup>1)</sup>

A. de Rújula and R. Röckl  
CERN, Geneva, Switzerland

#### ABSTRACT

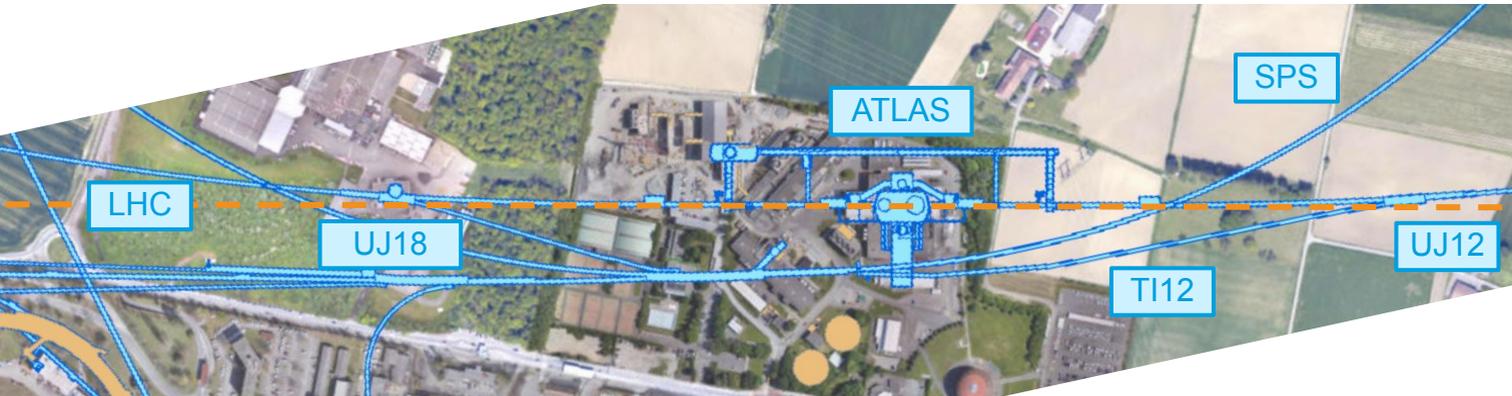
Extracted beams and fixed target facilities at future colliders (the SSC and the LHC) may be respectively improved by economic and "sociological" considerations. Neutrino and muon physics in the multi-TeV range would appear not to be an option for these machines. We partially reverse this conclusion by estimating the characteristics of the "prompt"  $\nu_\mu$ ,  $\nu_e$ ,  $\nu_\tau$  and  $\mu$  beams necessarily produced (or freed) at the pp or pp̄ interactions. The neutrino beams from a high luminosity pp̄ collider are not much less intense than the neutrino beams from the collider's dump, but require no main shielding. The same holds for the muon beams from the same machine. The same holds for the muon beams from the same machine. The same holds for the muon beams from the same machine. The physics program allowed by these lepton beams is a strong advocate of machines with the highest possible luminosity: pp (not pp̄) colliders.

#### 1. INTRODUCTION

The interactions of muons and muon-neutrinos with nucleons have not been experimentally studied with beams of energy in the TeV range. The  $\nu_\mu N$  interactions have been analyzed in detail only at energies characteristic of solar neutrinos. A single  $\nu_\mu$  has never been seen to interact in a detector. These are sufficient reasons to justify a  $\nu_\mu$ ,  $\nu_e$ ,  $\nu_\tau$  "program" at any future high energy facility, but one can say even more.

$$\Phi_0(\text{LHC}) = \frac{7.25 \cdot 10^6}{\text{sec}} (\mathcal{L} / 10^{33} \text{ cm}^{-2} \text{ sec}^{-1})$$

$$\Phi_0(\text{SSC}) = \frac{8.65 \cdot 10^6}{\text{sec}} (\mathcal{L} / 10^{33} \text{ cm}^{-2} \text{ sec}^{-1})$$

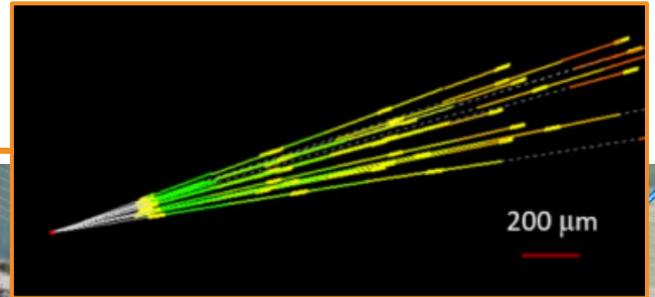


# First Neutrino Candidates.

In 2018, the FASER collaboration placed ~30 kg **pilot emulsion detectors** in T118 for a few weeks.  $O(10)$  neutrino interactions expected

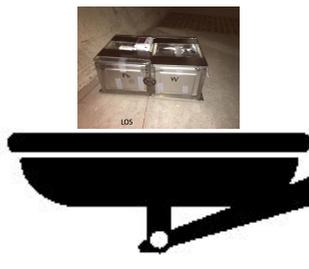
First neutrino interaction candidates were **recently reported**.

[FASER, 2105.06197]



# First Neutrino Candidates.

FASER Pilot Detector  
suitcase-size, 4 weeks  
\$0 (recycled parts)  
6 neutrino candidates

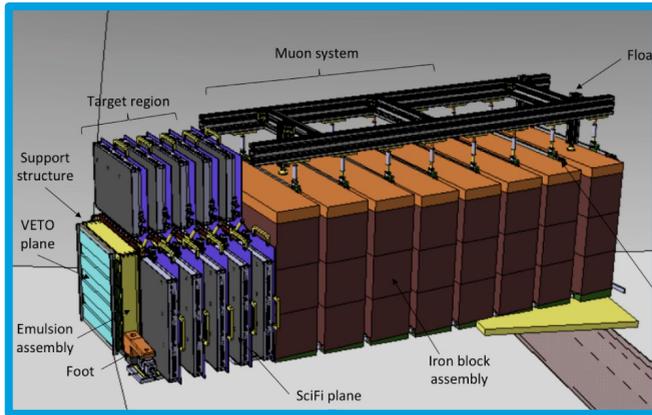


all previous collider detectors  
building-size, decades ~\$1B  
0 neutrino candidates

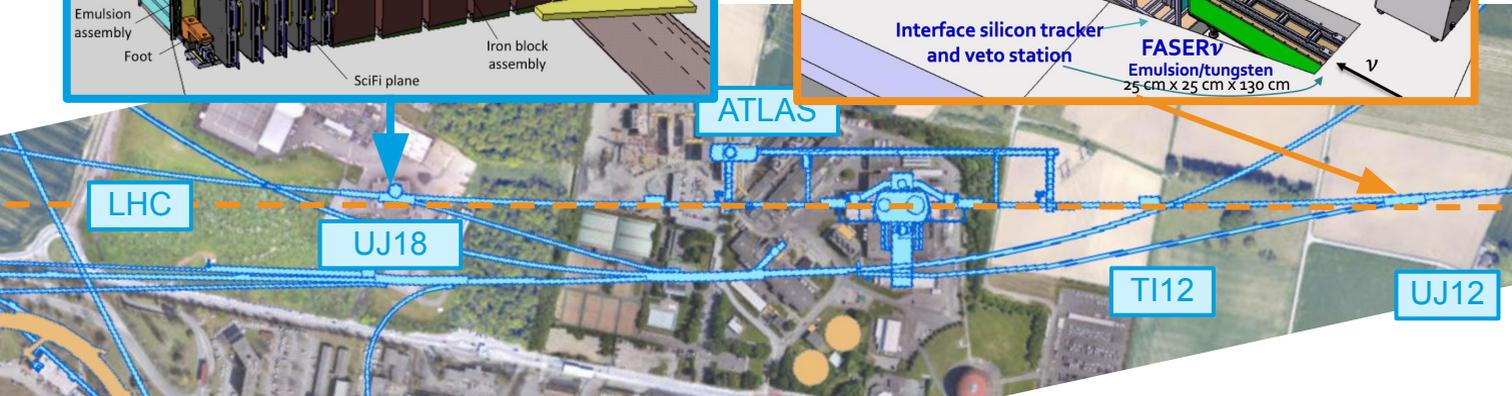
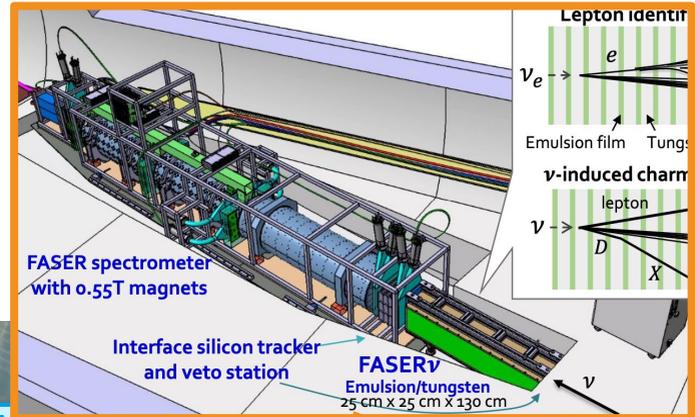
# New LHC Experiments during Run 3.

During Run 3 of the LHC, two new experiments will detect LHC neutrinos

## SND@LHC



## FASERv



# New LHC Experiments during Run 3.

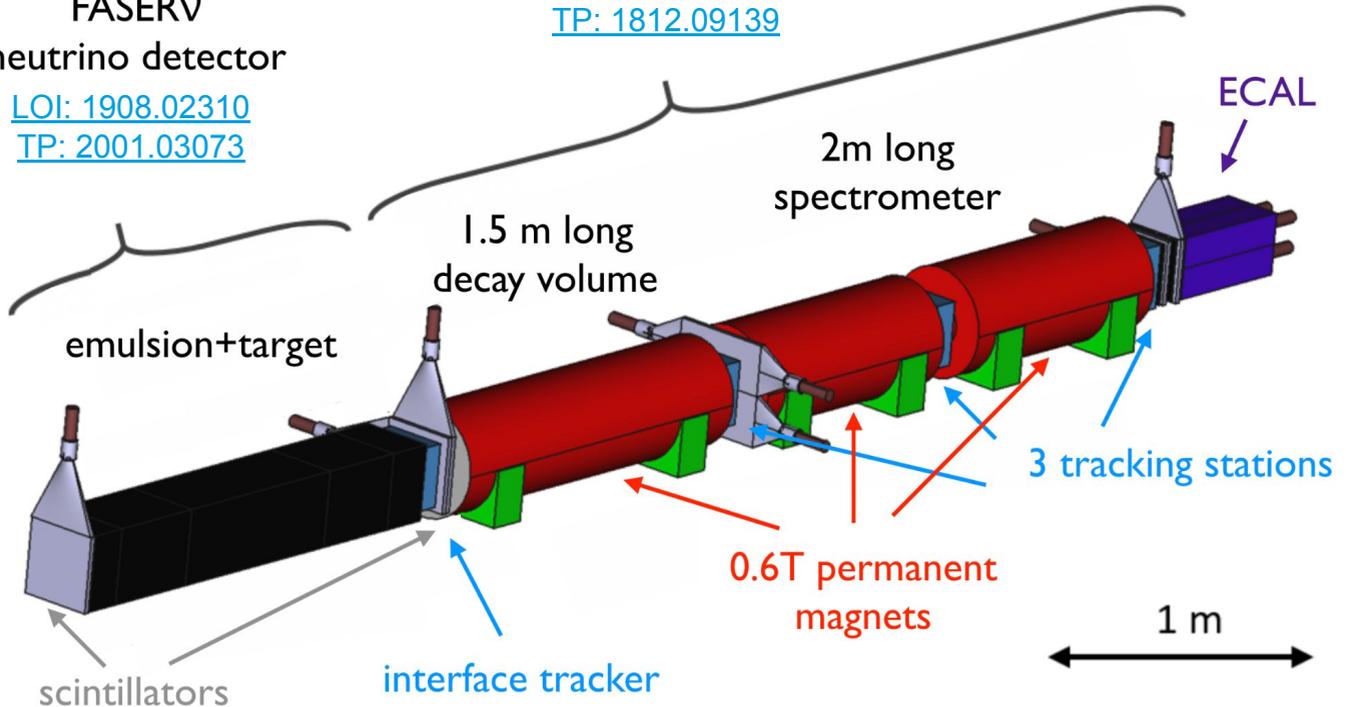


FASERv  
neutrino detector

[LOI: 1908.02310](#)  
[TP: 2001.03073](#)

FASER main detector

[LOI: 1811.10243](#)  
[TP: 1812.09139](#)



# New LHC Experiments during Run 3.

Thanks to the generous funding by the Heising-Simons Foundation, the Simons Foundation and CERN



2022-2024:  
Operation



2020/2021:  
Construction

**FASEr**

77 collaborators  
21 institutions  
9 countries

03/2019:  
Approval and Funding

**CERN Bulletin** Issue No. 13 | 19/03/21 | Thursday 23 March 2021  
New articles: #CERN | [https://cern.ch/cern-bulletin](#)

**LS2 REPORT: FASER IS BORN**

**A WORD FROM CHARLOTTE LINDBERG WARAKAULLE**

EXCELLENCE IN SCIENCE  
THRIVES ON GLOBAL INTERACTION

FASER, the Forward Search Experiment, has been installed in the LHC tunnel during Long Shutdown 2. It is currently being tested and will start taking data next year

08/2017:  
Idea

**PHYSICS TODAY**

**A small detector could strike big in the search for dark matter**

Low cost, spare parts, private money, and further serendipity converged to accelerate a new experiment at the LHC.

**FASEr**

**FASEr: CERN approves new experiment to look for long-lived, exotic particles**

The experiment, which will complement existing searches for dark matter at the LHC, will be operational in 2021.

7 MARCH, 2019 | By Cristina Agrigona

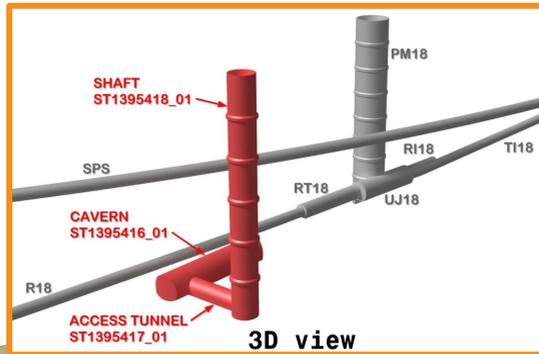


# Example: Neutrinos at the LHC.

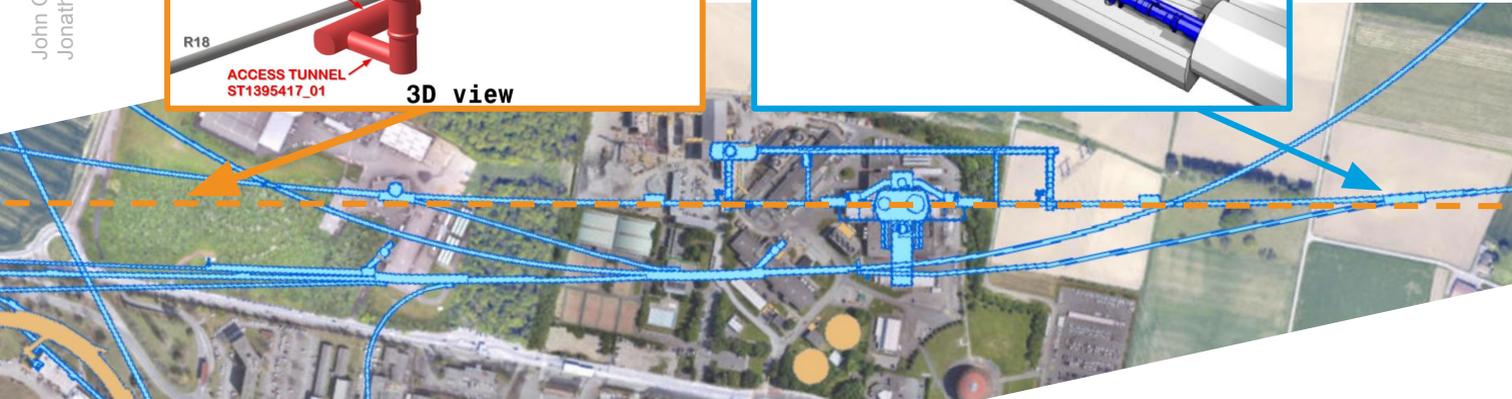
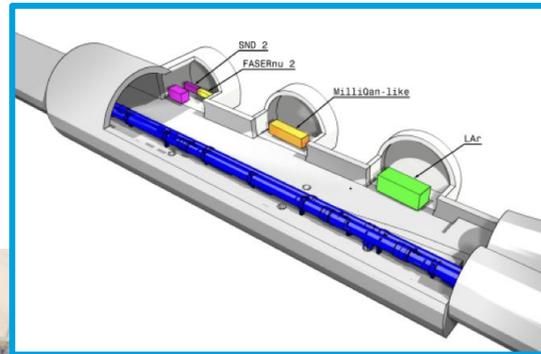
FASER and SND@LHC are currently highly constrained by 1980's infrastructure that was never intended to support experiments

The proposal: create a Forward Physics Facility (FPF) for the HL-LHC to house a suite of experiments. Two promising locations were identified.

## Purpose Built Facility



## UJ12 Alcove Extension



# Forward Physics Facility.

The FPF would house a suite of experiments that will greatly enhance the LHC's physics potential for **BSM physics searches**, **neutrino physics** and **QCD**.

## FASER2

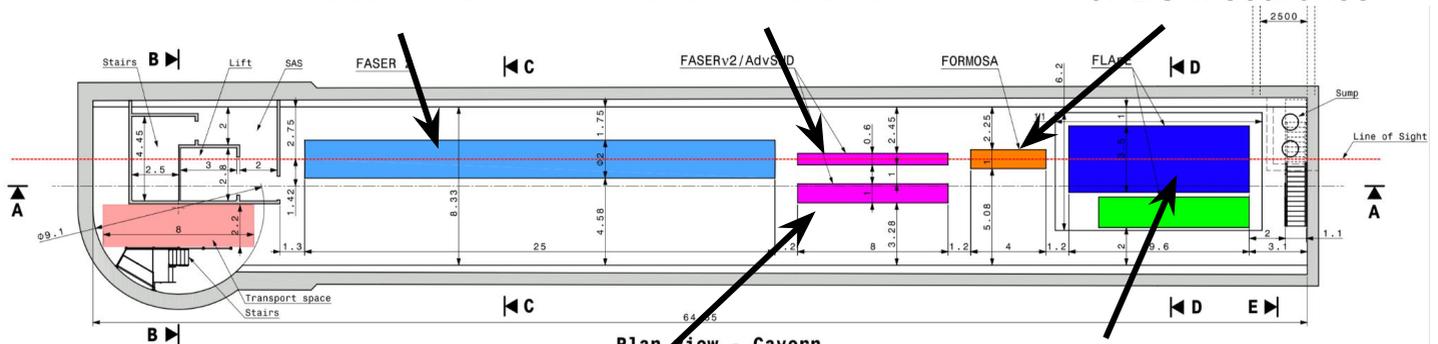
magnetized spectrometer  
for BSM searches

## FASERv2

emulsion-based  
neutrino detector

## FORMOSA

plastic scintillator array  
for BSM searches



Plan view - Cavern  
1:100

**AdvSND**  
electronic  
neutrino detector

**FLArE**  
LAr based  
neutrino detector

# Forward Physics Facility.

Three dedicated PPF workshops:

November 2020: <https://indico.cern.ch/event/955956>

May 2021: <https://indico.cern.ch/event/1022352>

October 2021: <https://indico.cern.ch/event/1076733/>

Results summarized in paper discussing the **facility, proposed experiments** and physics potential for **BSM Physics, Neutrinos, QCD** and **Astroparticle Physics**.

~75 pages, written over last ~3month by ~80 authors

arXiv: [2109.10905](https://arxiv.org/abs/2109.10905)

## The Forward Physics Facility: Sites, Experiments, and Physics Potential

Luis A. Anchordoqui,<sup>1,\*</sup> Akitaka Ariga,<sup>2,3</sup> Tomoko Ariga,<sup>4</sup> Weidong Bai,<sup>5</sup> Kincsó Balazs,<sup>6</sup> Brian Batell,<sup>7</sup> Jamie Boyd,<sup>8</sup> Joseph Bramante,<sup>8</sup> Adrian Carmona,<sup>9</sup> Mario Campanelli,<sup>10</sup> Francesco G. Celiberto,<sup>11,12,13</sup> Grigorios Chachamis,<sup>14</sup> Matthew Citron,<sup>15</sup> Giovanni De Lellis,<sup>16,17</sup> Albert de Roeck,<sup>6</sup> Hans Dembinski,<sup>18</sup> Peter B. Denton,<sup>19</sup> Antonia Di Crescenzo,<sup>16,17,6</sup> Milind V. Divan,<sup>20</sup> Liam Dougherty,<sup>21</sup> Herbi K. Dreiner,<sup>22</sup> Yong Du,<sup>23</sup> Rikard Enberg,<sup>24</sup> Yasaman Farzan,<sup>25</sup> Jonathan L. Feng,<sup>26,†</sup> Max Fieg,<sup>26</sup> Patrick Foldenauer,<sup>27</sup> Saïd Foroughi-Abari,<sup>28</sup> Alexander Friedland,<sup>29,\*</sup> Michael Fucilla,<sup>30,31</sup> Jonathan Gall,<sup>32</sup> Maria Vittoria Garzelli,<sup>33,†</sup> Francesco Giuli,<sup>34</sup> Victor P. Gonçalves,<sup>35</sup> Marco Guzzi,<sup>36</sup> Francis Halzen,<sup>37</sup> Juan Carlos Helo,<sup>38,39</sup> Christopher S. Hill,<sup>40</sup> Ahmed Ismail,<sup>41,\*</sup> Ameen Ismail,<sup>42</sup> Sudip Jana,<sup>43</sup> Yu Seon Jeong,<sup>44</sup> Krzysztof Jodłowski,<sup>45</sup> Fnu Karan Kumar,<sup>20</sup> Kevin J. Kelly,<sup>46</sup> Felix Kling,<sup>29,47,‡</sup> Rafal Maciula,<sup>48</sup> Roshan Mammen Abraham,<sup>41</sup> Julien Manshanden,<sup>33</sup> Josh McFayden,<sup>49</sup> Mohammed M. A. Mohammed,<sup>30,31</sup> Pavel M. Nadolsky,<sup>50,\*</sup> Nobuchika Okada,<sup>51</sup> John Osborne,<sup>6</sup> Hidetoshi Otono,<sup>4</sup> Vishvas Pandey,<sup>52,46,\*</sup> Alessandro Papa,<sup>30,31</sup> Digesh Raut,<sup>53</sup> Mary Hall Reno,<sup>54,\*</sup> Filippo Resnati,<sup>6</sup> Adam Ritz,<sup>28</sup> Juan Rojo,<sup>55</sup> Ina Sarcevic,<sup>56,\*</sup> Christiane Scherb,<sup>57</sup> Pedro Schwaller,<sup>58</sup> Holger Schulz,<sup>59</sup> Dipan Sengupta,<sup>60</sup> Torbjörn Sjöstrand,<sup>61,\*</sup> Tyler B. Smith,<sup>26</sup> Dennis Soldin,<sup>53,\*</sup> Anna Stasto,<sup>62</sup> Antoni Szczurek,<sup>48</sup> Zahra Tabrizi,<sup>63</sup> Sebastian Trojanowski,<sup>64,65</sup> Yu-Dai Tsai,<sup>26,46</sup> Douglas Tucker,<sup>66</sup> Martin W. Winkler,<sup>67</sup> Keping Xie,<sup>7</sup> and Yue Zhang<sup>66</sup>

The Forward Physics Facility (FPF) is a proposal to create a cavern with the space and infrastructure to support a suite of far-forward experiments at the Large Hadron Collider during the High Luminosity era. Located along the beam collision axis and shielded from the interaction point by at least 100 m of concrete and rock, the PPF will house experiments that will detect particles outside the acceptance of the existing large LHC experiments and will observe rare and exotic processes in an extremely low-background environment. In this work, we summarize the current status of plans for the PPF, including recent progress in civil engineering in identifying promising sites for the PPF; the PPF experiments currently envisioned to realize the PPF's physics potential; and the many Standard Model and new physics topics that will be advanced by the PPF, including searches for long-lived particles, probes of dark matter and dark sectors, high-statistics studies of TeV neutrinos of all three flavors, aspects of perturbative and non-perturbative QCD, and high-energy astroparticle physics.

Experimental Program:

FASER - FASER $\nu$  - SND@LHC - FPF

**Searches for BSM physics:**

**LLPs - DM - mCPs**

SM Measurements:

Neutrinos - QCD - Cosmic Rays

# Motivation: Dark Sectors.



Simple Model: Dark Matter charged under  $U(1)_D$

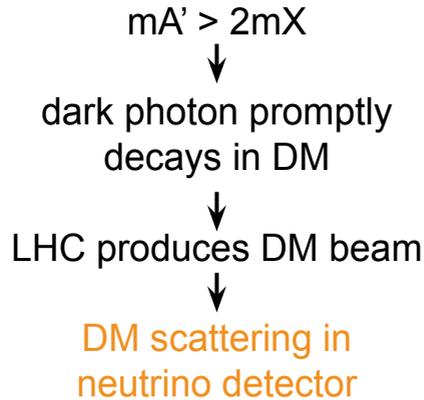
$$\mathcal{L} \supset -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} m_{A'}^2 A'^2 - m_\chi^2 \chi^2 - ig_D A' \chi^2$$

coupling to SM via small mixing with SM photon

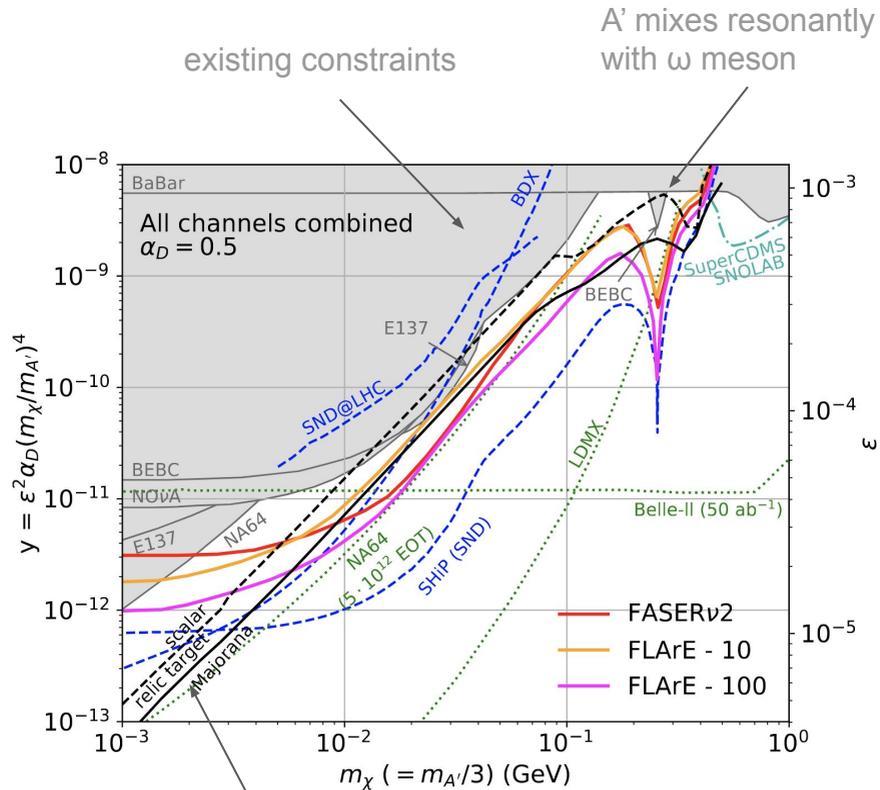
massive gauge boson:  
dark photon

dark photon couples to DM

# Dark Matter Scattering.



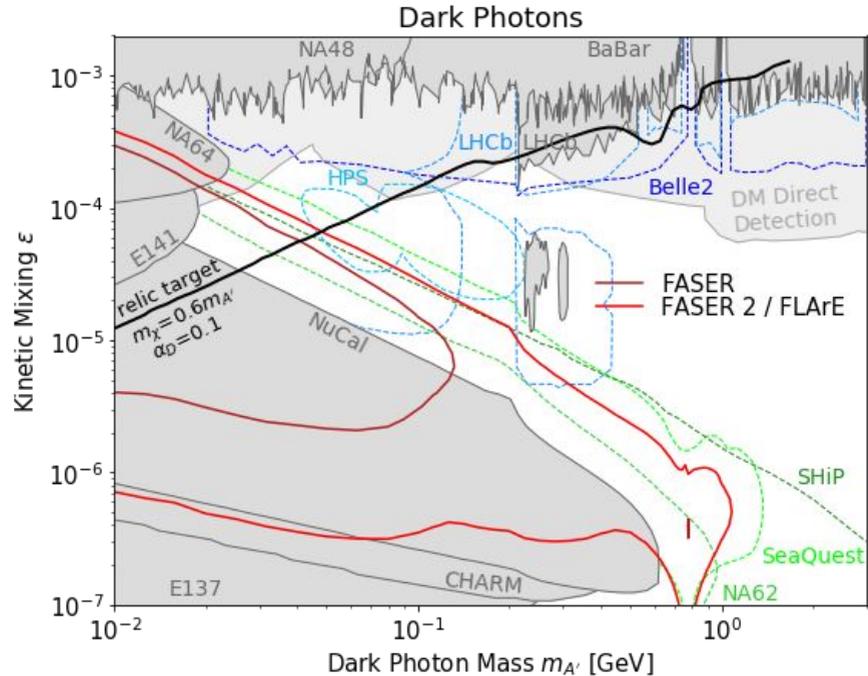
for more details see: [2101.10338](https://arxiv.org/abs/2101.10338)



where we would expect DM in this model

# Long-Lived Particles.

If  $m_{A'} < 2m_X$   
↓  
 $A'$  decays to SM particles  
↓  
Long lived particle decays

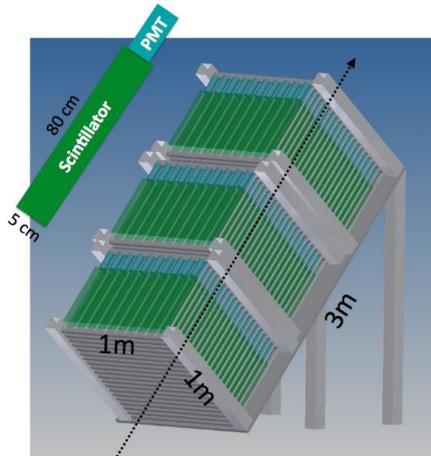


For details and many more models see [1811.12522](https://arxiv.org/abs/1811.12522).

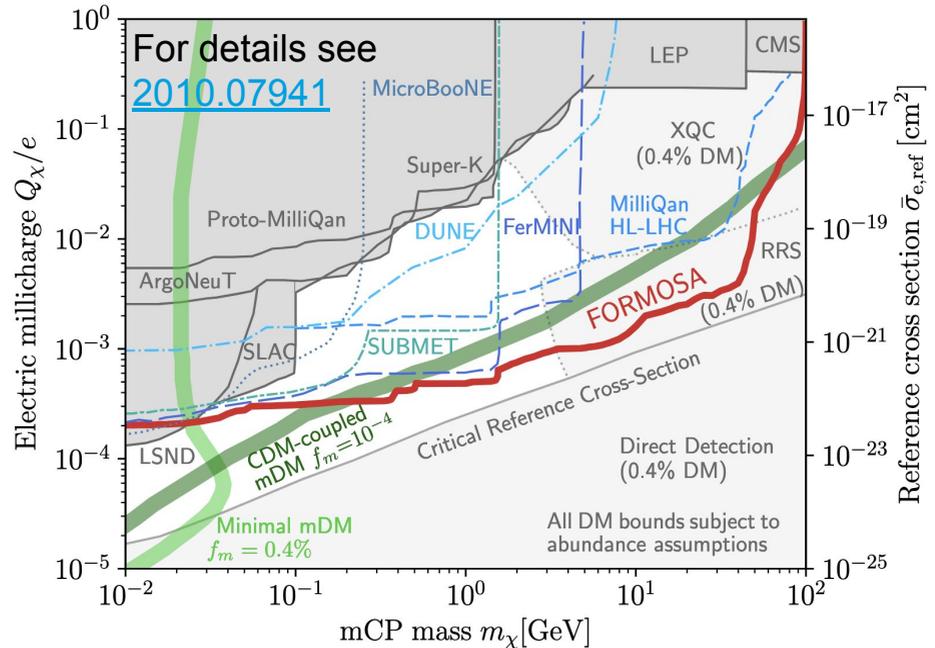
# MilliCharged Particles.

If  $m_A=0$ :  $X$  is effectively **milli-charged** with  $Q=\epsilon e \rightarrow$  search for minimum ionizing particle with very small  $dE/dx$

MilliQan was proposed as dedicated LHC experiment to search for MCPs near CMS.  
But it was noted that signal flux is  $\sim 100$  times larger in forward direction.

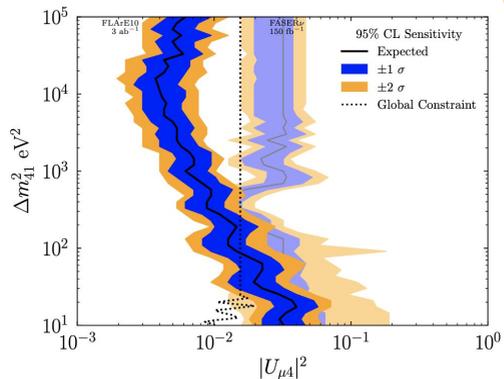
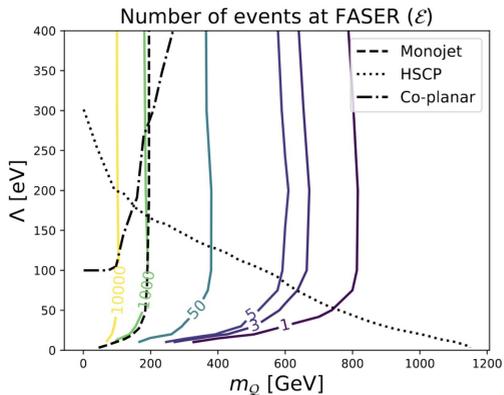


milliQan detector: [1607.04669](#)



# More Ideas.

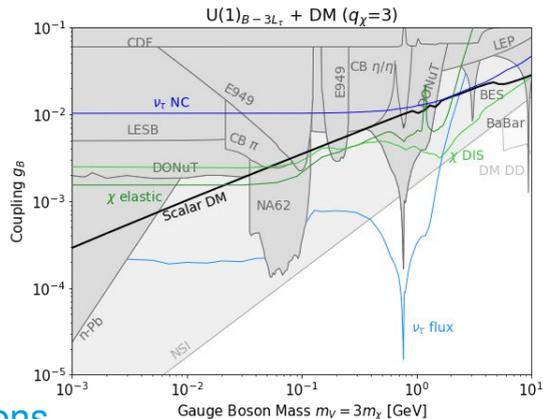
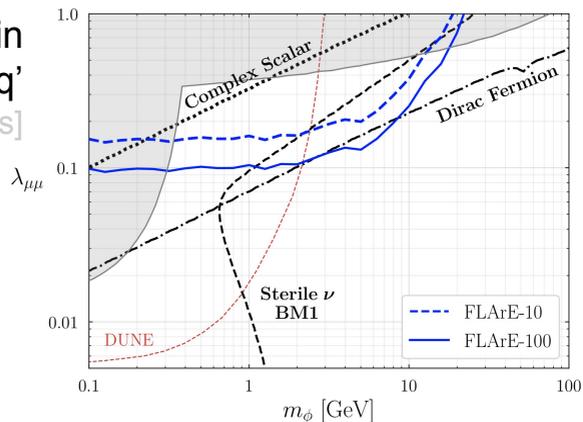
neutrino-philic dark matter production in  
neutrino interactions  $\nu q \rightarrow \phi | q'$   
[Kelly, Kling, Tuckler, Zhang, in progress]



Quirks via  
nonstandard tracks  
[2108.06748]

light tau-neutrino philic  
mediators: modified fluxes  
and interactions  
[Batell et al, in progress]

Sterile Neutrino Oscillations  
[performed by Peter Denton]



Experimental Program:

FASER - FASER $\nu$  - SND@LHC - FPF

Searches for BSM physics:

LLPs - DM - mCPs

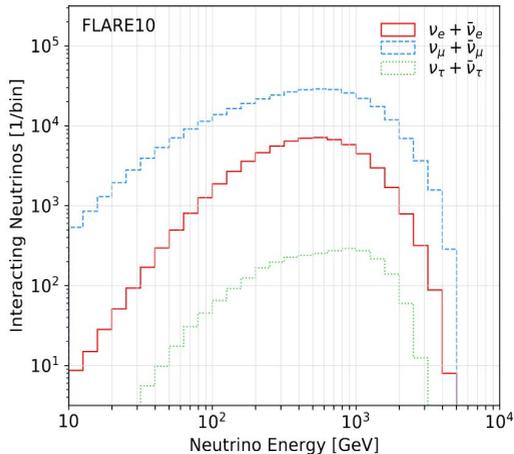
**SM Measurements:**

**Neutrinos - QCD - Cosmic Rays**

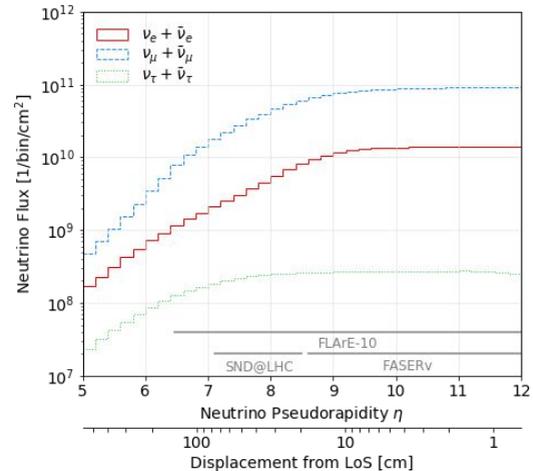
# Neutrino Fluxes and Rates.

ATLAS produces an **intense**, **highly energetic** and **strongly collimated** neutrino beam of all three flavours in the far forward direction.

energy spectrum of  
interacting neutrinos



neutrino flux as function  
of displacement from LoS



100 GeV - few TeV energies

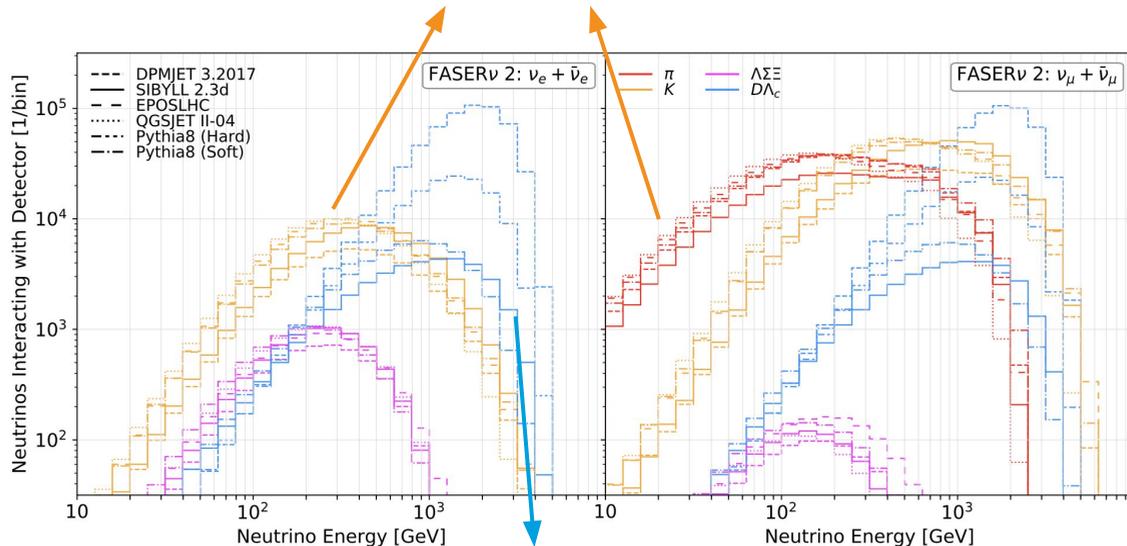
flux peaked around LoS, start to drop around 1m away from LoS

complementary coverage of FASERv and SND@LHC

# Neutrino Production.

Forward particle production is poorly constrained by other LHC experiments. The measurement of neutrinos fluxes at the FPF will provide novel complimentary constraints on forward particle production.

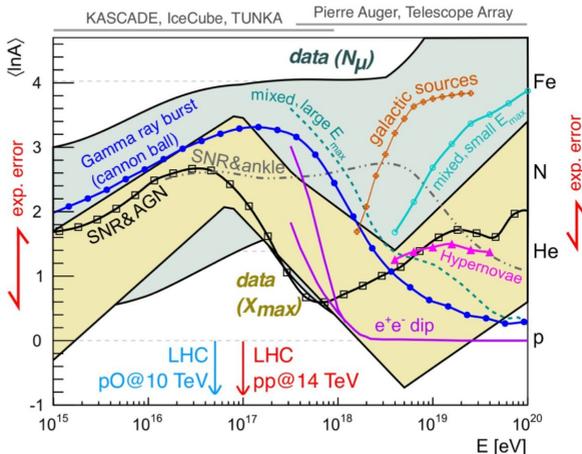
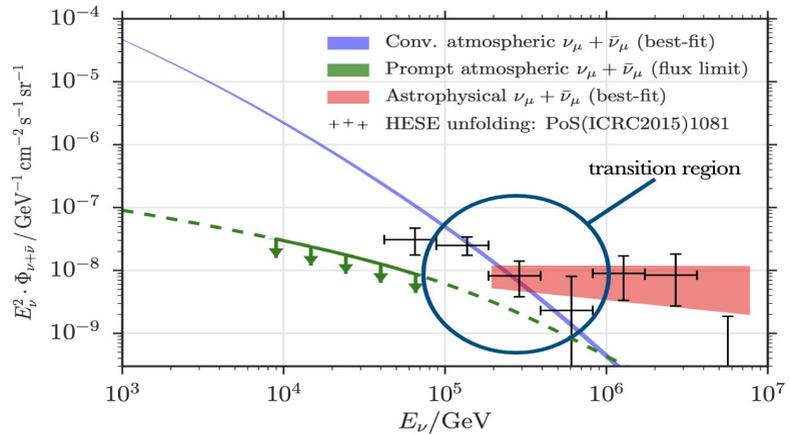
**pions & kaons:** improve MC generators, cosmic ray muon puzzle



**charm:** perturbative QCD, test transition to small-x factorization, constrain low-x gluon PDF, probe gluon saturation, probe intrinsic charm, constrain prompt atmospheric neutrino flux at IceCube.

# Neutrino Production.

Measuring forward charm production at the LHC would help to constrain the (currently very poorly constrained) prompt atmospheric neutrino flux at IceCube.

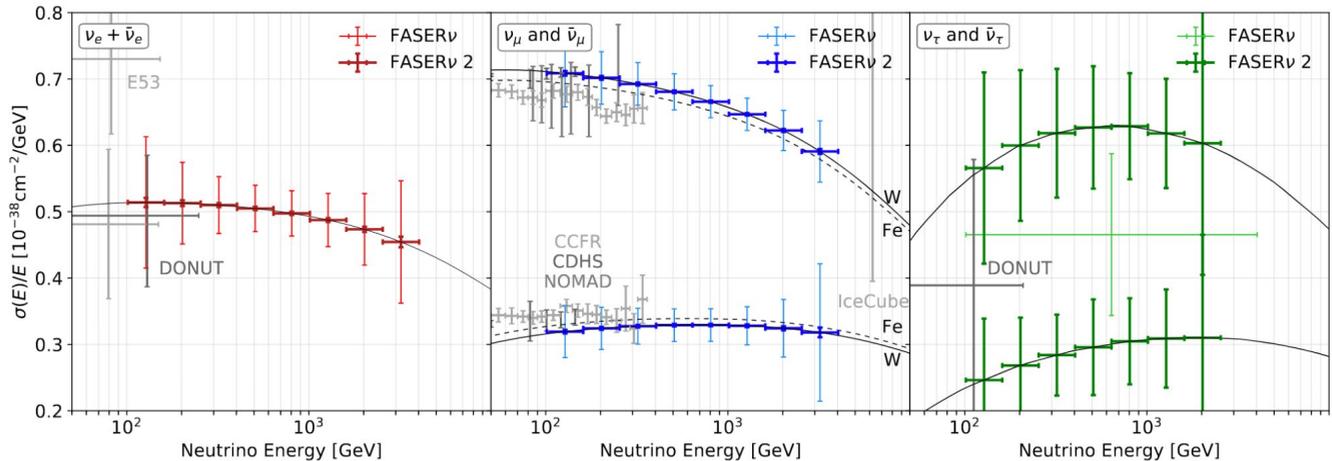


Cosmic Ray experiments have reported an excess in the number of muons over expectations computed using extrapolations of hadronic interaction models tuned to LHC data at the few  $\sigma$  level (**muon problem in CR physics**).

Measurements of forward hadron production (kaons) at the LHC are crucial to solve this issue.

# Neutrino Interactions.

Using LHC neutrinos, one can measure **neutrino cross section** at unexplored TeV energies for all three flavors. Both CC and NC are possible.

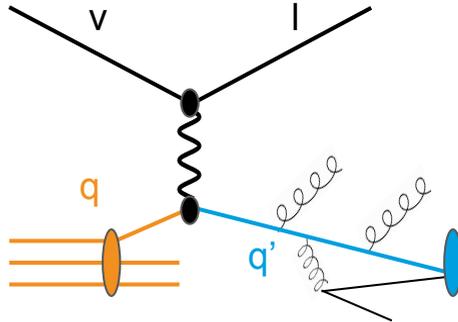


statistical uncertainty only

FASER $\nu$  will detect  $\sim 10$  **tau neutrino interactions**, which is similar to DONuT and OPERA. Thousands of tau neutrino events possible at HL-LHC, allowing for precision studies of tau neutrino properties.

# Neutrino Interactions.

The FPF is essentially a Neutrino-Ion collider with  $\sqrt{s} \sim 50 \text{ GeV}$



## Initial State

nuclear PDFs via measurements  
on different targets

strange quark PDFs  
via  $\nu s \rightarrow l c$

EMC effect for neutrinos

## Final State

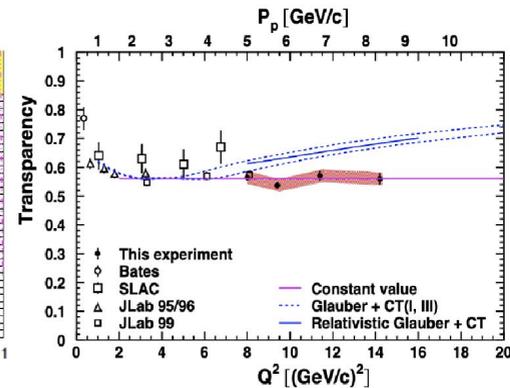
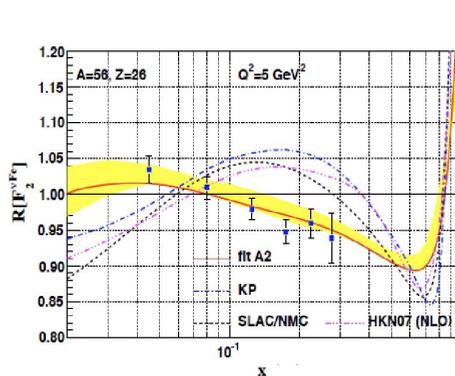
response of cold nuclear matter to  
fast moving quarks

medium-induced energy losses

fragmentation functions

final state interactions

color transparency



# Summary.

---

With FASER and SND@LHC, the first experiments will soon start to perform searches for new particles and neutrino measurements in the far-forward region of the LHC.

We propose to continue this program with improved detectors as part of a Forward Physics Facility at the HL-LHC. This will open up many many new opportunities for **BSM physics searches**, **neutrino physics** and **QCD**, significantly extending the LHC's physics program.



**We would like to invite the HEP community to help us explore and better understand the physics potential of this program.**

You are welcome to join!

For questions and comments, please contact me via [felix.kling@desy.de](mailto:felix.kling@desy.de)

**Backup.**

# Location.

We can't place a reasonably-sized detector on the beam line near the IP

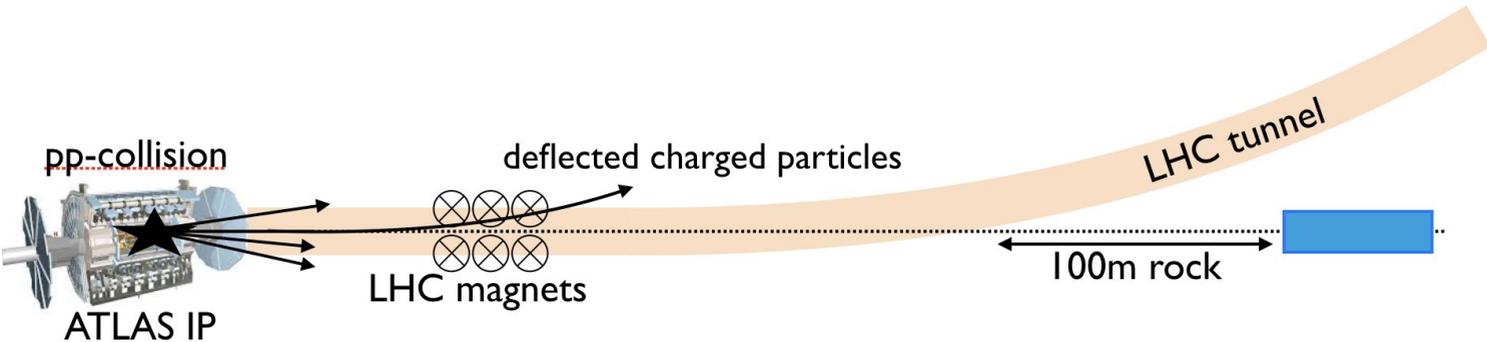
- \* blocks the proton beams, subject to large radiation

However, weakly-interacting particles do not interact with matter

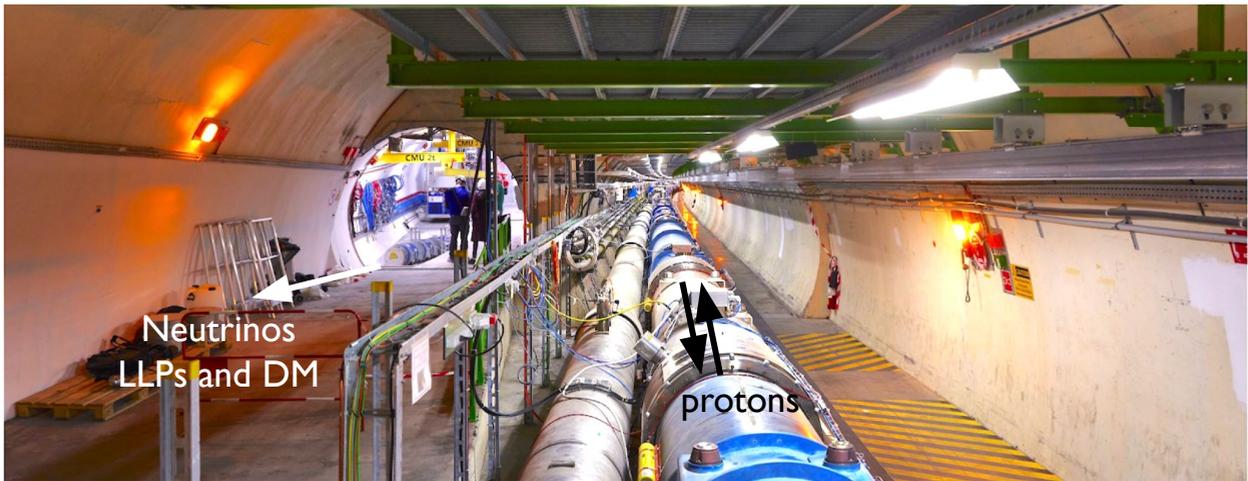
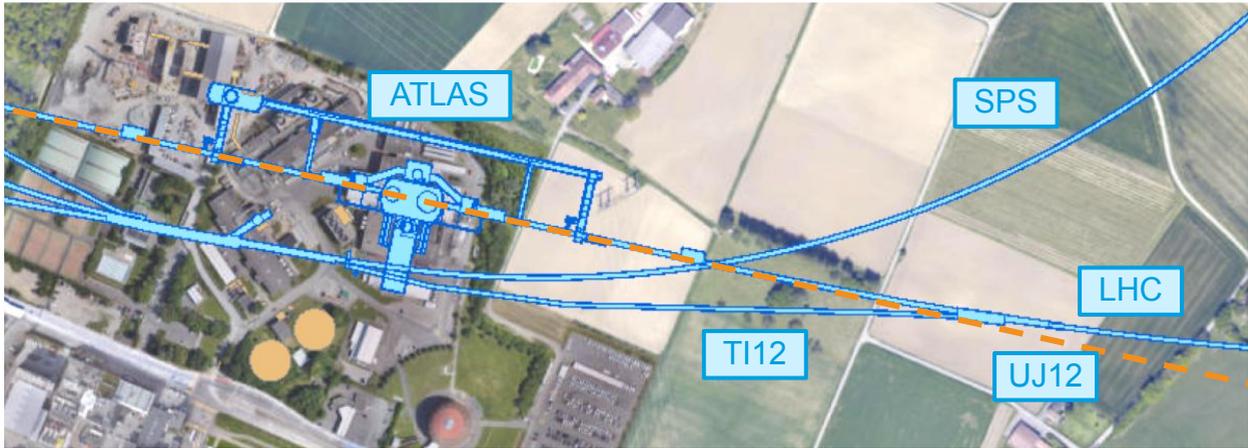
- \* place detector few 100m away along the "collision axis" after beam curves
- \* LHC infrastructure acts and rock act as shielding

At this location, particles are still highly collimated

- \* 100m x mrad  $\sim$  10cm spread in transverse plane



# Location.



# FASER Detector.

**Main Goal: Search for light long-lived particles**

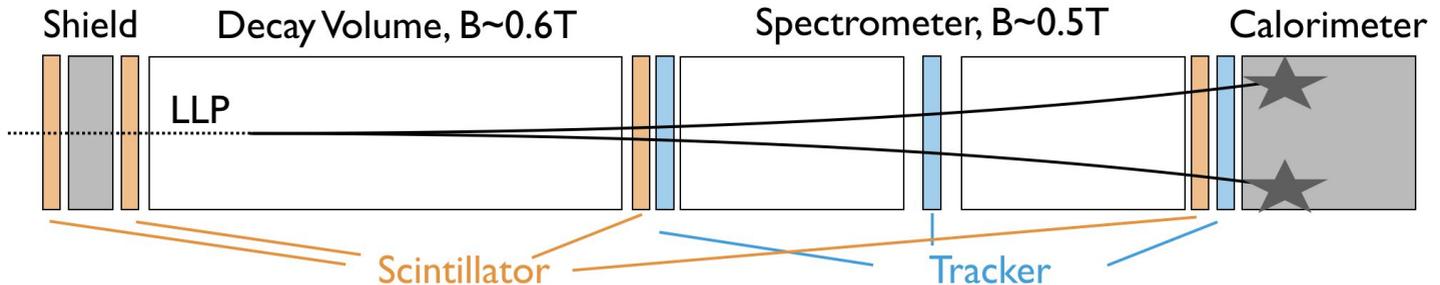
$pp \rightarrow \text{LLP} + X$ , LLP travels  $\sim 480\text{m}$ ,  $\text{LLP} \rightarrow \text{charged tracks} + X$

## Signal is striking:

- \* two opposite-sign, high energy ( $E > 500 \text{ GeV}$ ) charged particles
- \* originate from a common vertex in a small, empty decay volume
- \* point back to the IP through 90 m of rock

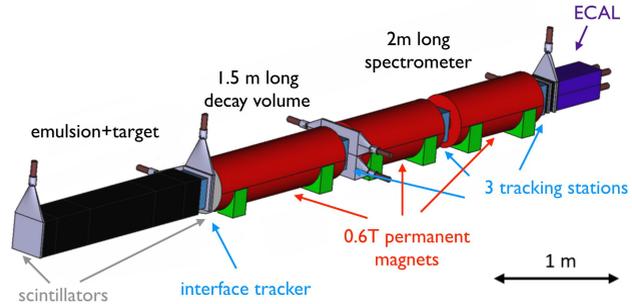
## Background considerations:

- \* cosmic rays and neutrino interactions (different kinematics) not a problem
- \* HE muon-associated radiative events are leading BG if muon is not vetoed
- \* incoming muons can be identified using scintillators  
→ reduce BG to negligible levels



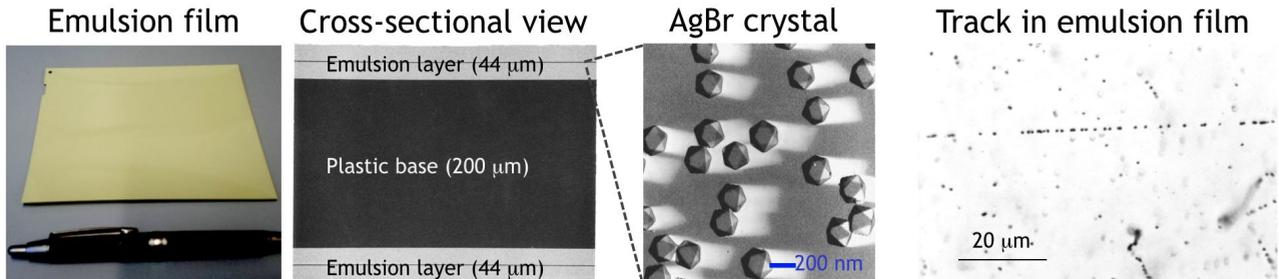
## FASERv neutrino detector in front of FASER

- \* 25cm x 25cm x 1.3m emulsion detector
- \* tungsten target with 1.2 ton mass
- \* placed on-axis:  $\eta > 9$  angular coverage
- \*  $\sim 1000 \nu_e$ ,  $\sim 10000 \nu_\mu$ ,  $\sim 10 \nu_\tau$  during LHC Run 3



## Emulsion detectors technology

- \* used by many other neutrino experiments: CHORUS, DONUT, OPERA
- \* 1000 emulsion films interleaved with 1mm tungsten plates
- \* 3D tracking devices with 50 nm spatial precision
- \* global reconstruction with the FASER detector possible



emulsion detectors allow for:  
neutrino search via neutral vertices  
lepton flavour identification  
energy measurement via MCS

charged track

photon

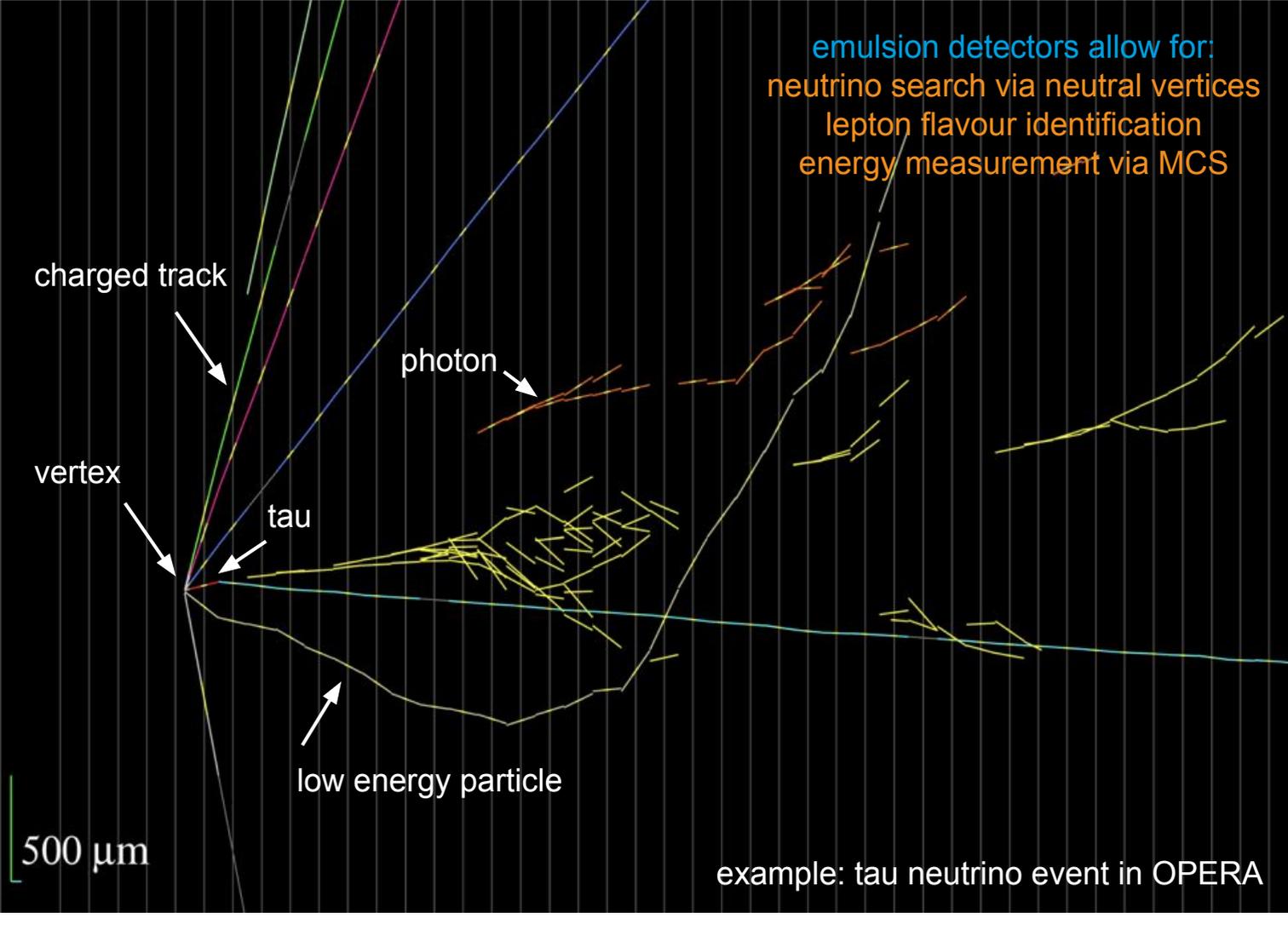
vertex

tau

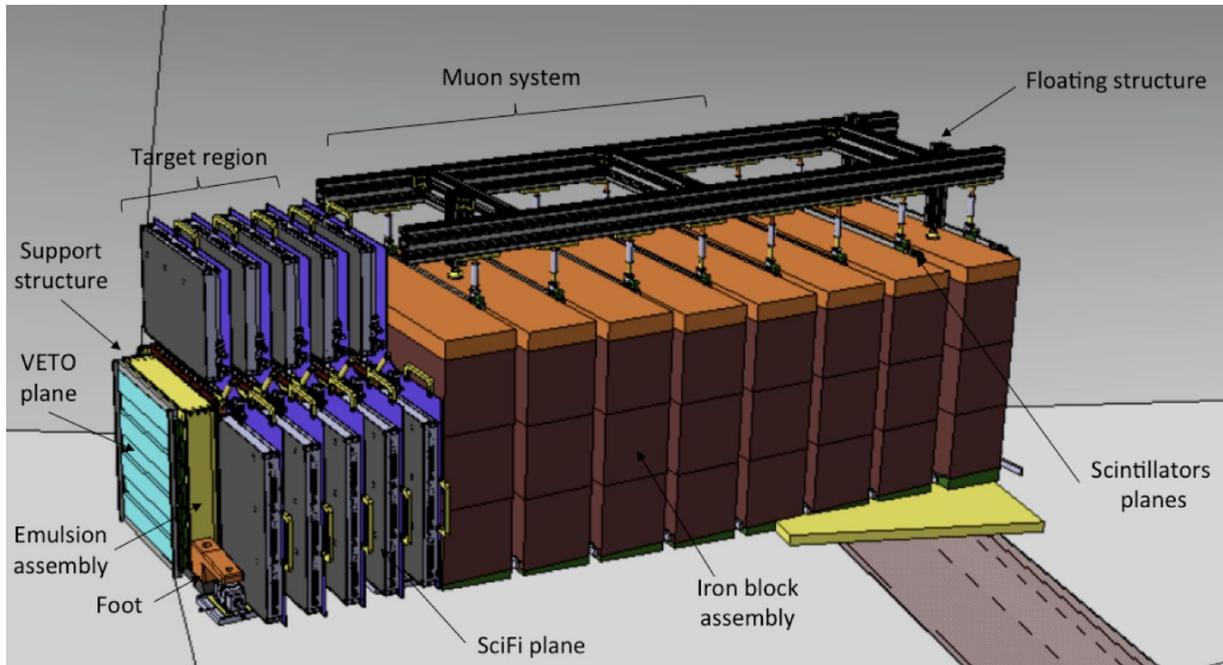
low energy particle

500  $\mu\text{m}$

example: tau neutrino event in OPERA



contains both emulsion and electronic components  
off-axis location:  $7.2 < \eta < 8.7$  angular coverage  
target: 830 kg of tungsten



# Neutrino Fluxes and Rates.

Event rates at LHC neutrino experiments  
estimated with two LO MC generators: SIBYLL / DPMJET

Detector			Number of CC Interactions			
Name	Mass	Coverage	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	
LHC Run3	FASER $\nu$	1 ton	$\eta \gtrsim 8.5$	1.3k / 4.6k	6.1k / 9.1k	21 / 131
	SND@LHC	800kg	$7 < \eta < 8.5$	180 / 500	1k / 1.3k	10 / 22
HL-LHC	FASER $\nu$ 2	20 tons	$\eta \gtrsim 8$	178k / 668k	943k / 1.4M	2.3k / 20k
	FLArE	10 tons	$\eta \gtrsim 7.5$	36k / 113k	203k / 268k	1.5k / 4k
	AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	6.5k / 20k	41k / 53k	190 / 754

Large spread in generator predictions:



**Challenge:** For neutrino physics measurement we need to quantify and reduce neutrino flux uncertainties

**Opportunity:** Forward neutrino flux measurement can help to improve our understanding of underlying physics.

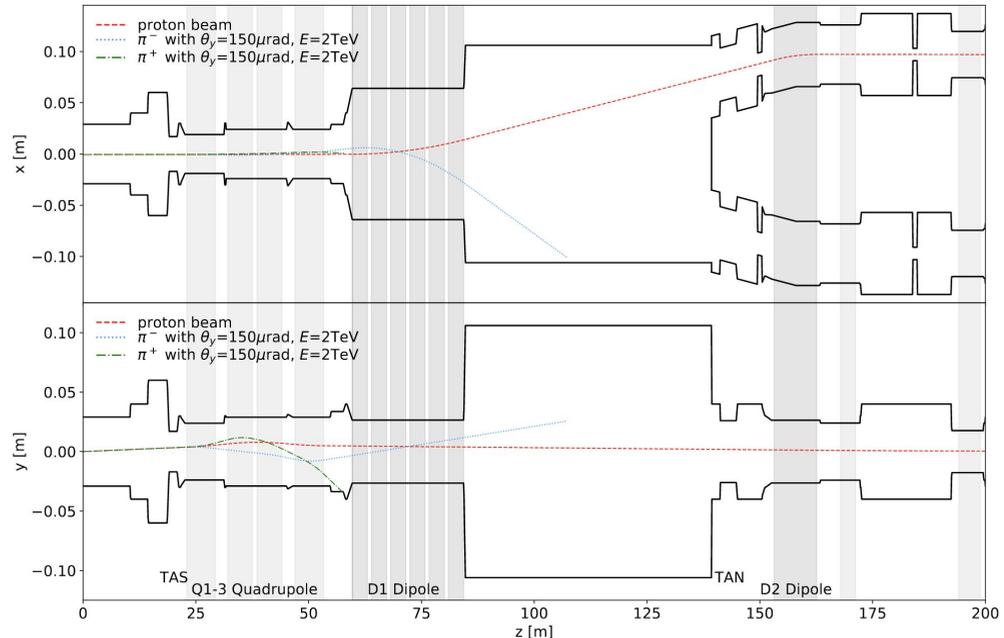
# Neutrino Fluxes and Rates.

The large majority of neutrino produced close to primary collisions inside the vacuum beam pipe. For those, one needs to model the propagation of hadrons through the LHC as well as their decays.

This has been realized as [fast neutrino flux simulation](#) implemented as RIVET module. [Kling, 2105.08270]

Procedure:

- 1) simulate collision with MC generator
- 2) propagate long-lived hadrons through LHC beam pipe and magnets
- 3) decay hadrons along their trajectory
- 4) fill neutrinos in histograms



# Neutrino Production.

Light hadron production is not described by pQCD

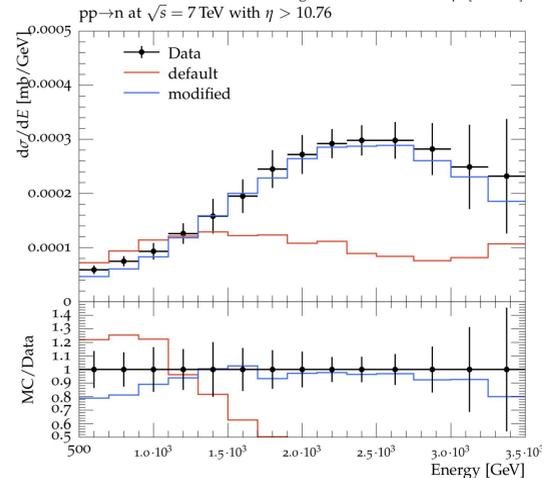
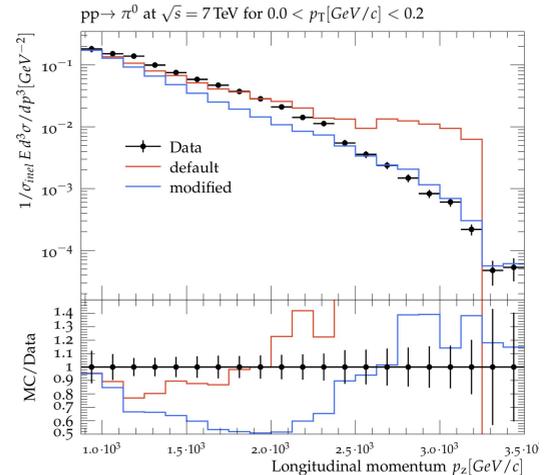
Use hadronic interaction models, often originating from CR physics.

Sophisticated description of microscopic physics with many phenomenological parameters tuned to data.

Currently: Use spread of generators as measure for uncertainty.

Proposal: create a dedicated forward physics tune in Pythia8 using LHCf measurements including tuning uncertainties (similar to PDF uncertainties)

[Fieg, Kling, Schulz, Sjostrand, in progress]



# Neutrino Production.

Neutrinos from charm decay could allow to test transition to **small-x factorization**, constrain **low-x gluon PDF**, probe **gluon saturation**, and probe **intrinsic charm**.

